Bulletin of the Seismological Society of America, Vol. 79, No. 2, pp. 330–341, April 1989

SLIP ON THE ELMORE RANCH FAULT DURING THE PAST 330 YEARS AND ITS RELATION TO SLIP ON THE SUPERSTITION HILLS FAULT

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ABSTRACT

The Elmore Ranch fault is a left-lateral fault that strikes northeast within the right-lateral transform boundary that strikes northwest through southern California. It lies transverse and adjacent to the segment of the Superstition Hills fault that ruptured in 1987. Rupture of the Elmore Ranch fault (M_S = 6.2) preceded rupture of the Superstition Hills fault (M_S = 6.6) by about 11.4 hr. The Elmore Ranch fault slipped at the surface in 1987 with left-lateral displacements of up to 130 mm. Geological data indicate that it had slipped prehistorically, sometime after about 1660 A.D., probably in a single event. Excavations at three sites enable the following comparisons:

	November 1987 (mm)	~1660–October 1987 (mm)
Main Strand	70 ± 5	230 ± 20
West Strand	30 ± 5	90 ± 10
East Strand	50 ± 10	<25 (?)
Total	150 ± 20	320 ± 30

At these sites, the only significant component of dip slip (down to the southeast) was found on the west strand for slip previous to 1987.

The Superstition Hills fault has also been documented to have experienced one slip event between ~1660 and 1987. Thus these slip events on the Elmore Ranch and Superstition Hills faults may have occurred in a sequence similar to that in 1987. Neither the main fault nor the cross-fault, however, appear to have exactly duplicated their previous surficial slip. Previous slip was probably smaller on the Superstition Hills fault and larger on the Elmore Ranch fault zone than in the 1987 event. Because the temporal correlation between previous slip events is not proven, rupture sequences other than a doublet in which main fault rupture follows cross-fault rupture are possible.

INTRODUCTION

The Elmore Ranch fault (Fig. 1) slipped at the surface in association with the Superstition Hills earthquake sequence of 24 November 1987 (Hudnut *et al.*, 1989b). The Elmore Ranch fault has several strands trending N30° to 45°E (Fig. 2), and their sense of slip in 1987 was dominantly left-lateral. Investigation of localities where these fault strands cut young sediments (numbered localities in Fig. 2) reveal that the Elmore Ranch fault slipped previously, during the past 330 years. Evidence for the previous slip is presented in this paper.

A previous earthquake on the Superstition Hills fault that also occurred during the past 330 years has been documented by Hudnut and Sieh (1989) and Lindvall *et al.*, (1989). This penultimate event on the Superstition Hills fault appears to have produced a smaller total offset across that main fault than the 1987 event if afterslip continues (Hudnut and Sieh, 1989). Interaction between rupture of the Elmore Ranch cross-fault and rupture of the main fault was clearly demonstrated in the 1987 earthquake sequence (Hudnut *et al.*, 1989a). This interaction may show their characteristic mode of rupture. Data presented in this paper are consistent with a

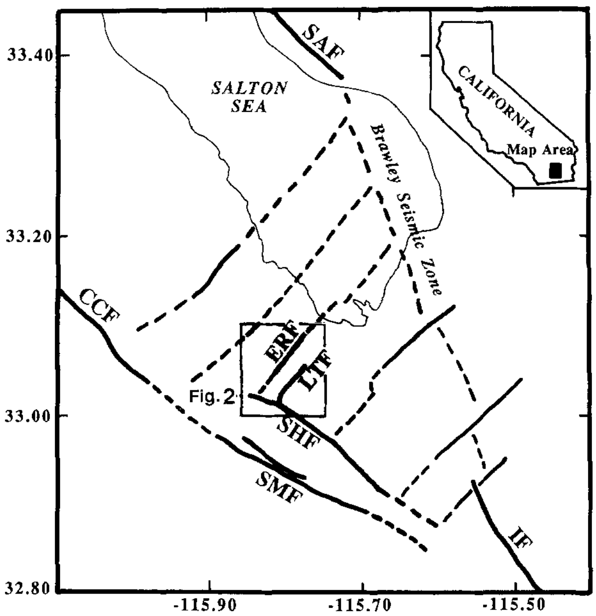

FIG. 1. Known and inferred faults in the vicinity of the study area. In November 1987, the Elmore Ranch fault (ERF) and Lone Tree fault (LTF) ruptured in association with a $M_S = 6.2$ event that occurred 11.4 hr before the $M_S = 6.6$ event on the Superstition Hills fault (SHF). Other fault names are abbreviated as follows: SAF, San Andreas fault; IF, Imperial fault; CCF, Coyote Creek fault; and SMF, Superstition Mountain fault.

characteristic doublet of events, but other possible relationships cannot be ruled out because the timing of penultimate events is only roughly constrained.

Lake Cahuilla Recessional Shoreline Berms

During the past 1000 years, ancient Lake Cahuilla repeatedly filled the Salton trough to a highstand level of about 12 to 13 m above mean sea level (Waters, 1983, Sieh, 1986). The most recent highstand occurred in 1663 ± 22 A.D., according to Sieh and Williams (1989). After this highstand the lake level receded at a rate of about 1.5 m/yr, because of evaporation and seepage (Waters, 1983; Sieh and Williams, 1989). As the lake receded from its latest highstand, it intermittently deposited beach berms. In the area north of the highstand shoreline shown on Figure 2, these berms are evident now as semi-continuous prisms of clastic sediments, usually unconformably atop the abrasion surface cut in the Late Pleistocene (?) Brawley formation.

Northeast of the Superstition Hills (Fig. 2), the most pronounced recessional berms are at elevations from 7 to 12 m above mean sea level (msl) and from 15 to 18 m below msl. The deposits near the highstand level are several meters thick in places where they overlie or are cut by the cross-faults. Where these faults cut the set of berms at lower elevation, 1987 displacements tended to be higher, and the berms are less than a meter thick. These lower elevation sites were preferable for our study because the sediments were thin, so that excavation could be done with hand tools instead of heavy equipment.

Four principal sites were identified and excavated; two on the main strand, and one each on the western and eastern strands of the Elmore Ranch fault (Fig. 2). Three of these (sites 1, 3, and 4 on Fig. 2) were in <1 m thick Lake Cahuilla recessional berm deposits between 15 and 18 m below sea level, where left-lateral slip in 1987 was ≧30 mm. The other (site 2) is near the highstand shoreline.

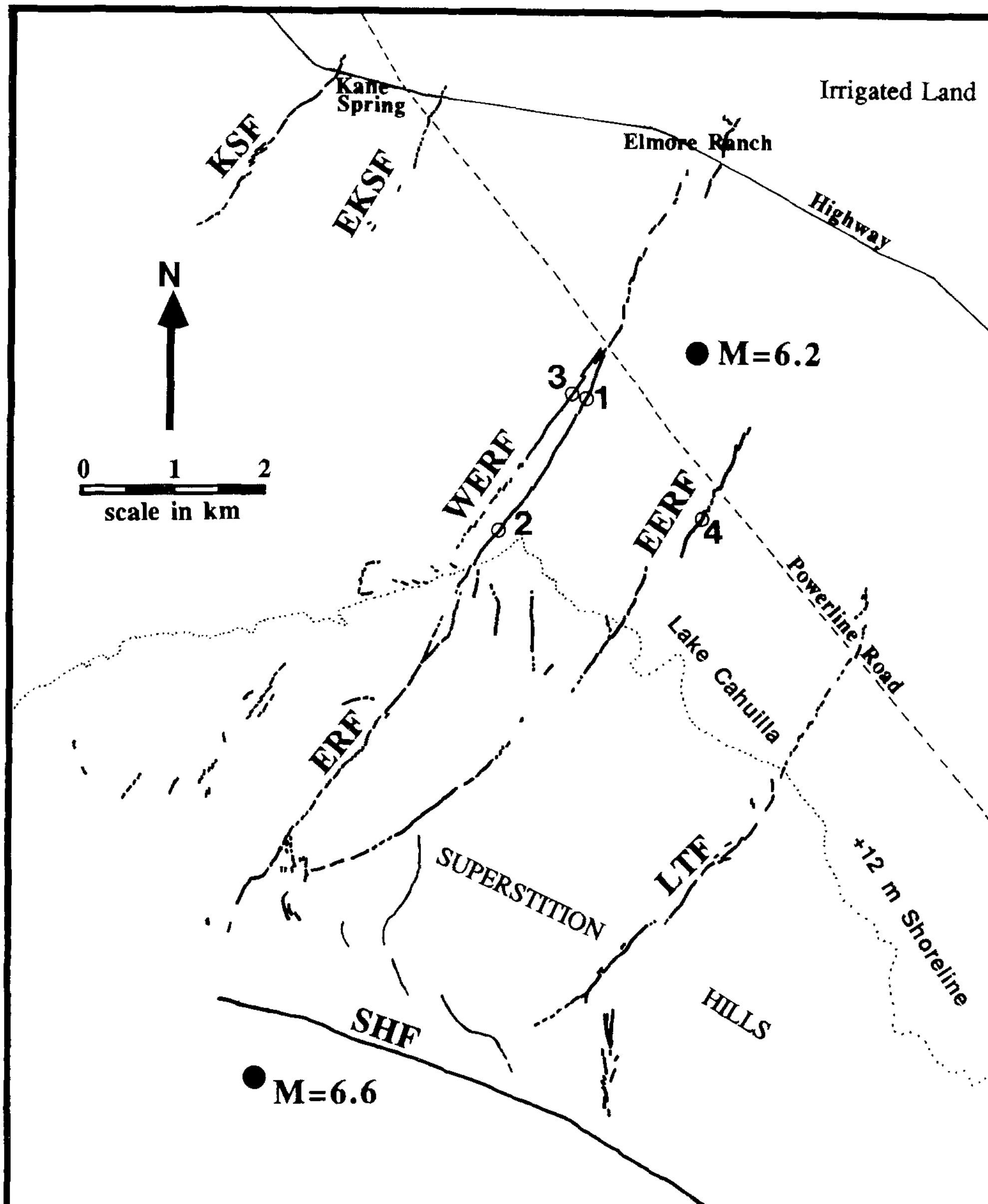

FIG. 2. Surface rupture traces on the cross-faults, as mapped by Hudnut *et al.* (1989b). Site numbers 1 through 4 identify trenching localities along strands of the Elmore Ranch fault zone that are described in this paper. Fault name abbreviations are the same as in Figure 1, and as follows: KSF, Kane Spring fault; EKSF, Eastern Kane Spring fault; WERF, Western Elmore Ranch fault; and EERF, Eastern Elmore Ranch fault. The approximate trace of the Lake Cahuilla shoreline during its latest highstand (at an elevation of 12 to 13 m above sea level) is identified as a dotted line. Trenching sites are below this elevation. Epicenters of the two largest events in the November 1987 sequence are also shown; absolute location errors for these are about ±2 km.

Age of Offset Geological Features

The geological features and deposits found to be offset by the fault strands are: (1) the planated surface of the Brawley formation, (2) sediments of the recessional berms, and (3) colluvium on top of the berm sands. Planation of the Brawley formation surface that has been offset to form pull-aparts probably was associated with the latest highstand of Lake Cahuilla, about 1663 ± 22 A.D (Sieh and Williams, 1989). The surface may have formed earlier than this, perhaps as the lake transgressed to its latest highstand, or possibly during earlier cycles of transgression and regression. The pull-apart features offsetting this surface are sharply defined, however, indicating they have not been reworked by later lake waters. If the recessional berms are remnants of an earlier highstand, they may have capped and protected the pull-aparts from degradation by the latest lake. We consider this unlikely because sediments in the berms do not appear reworked. Because the abrasion surface in the vicinity of the study sites is not veneered bv other lake deposits, the surface would have been exposed to erosion by the latest transgression and regression. The surface was almost surely modified and attained a new configuration in association with the lastest highstand. Thus, although the evidence is indirect, the age of this surface probably roughly equals the age of the latest highstand.

Within the recessional berms, sandy beds locally show offlapping relations to this surface, but these intersections were never distinct enough to form useful piercing points. The berm sands are, however, observed to have been disrupted and to have fallen into the fractures that formed in the Brawley formation. The disruption of bedding and laminae proves that the berm sediments were in place before the fractures formed. The berm deposits at these sites have not been directly dated. It is unlikely, however, that such thin packets of coarse sediment could survive a transgression and regression of the lake, as would be required if they were deposited during recession from the second-to-last highstand. It is thus most likely that these berms formed during recession of the lake from its latest highstand.

Colluvium overlies the berm sands and also fills the collapse features over fractures in the Brawley formation. The colluvium consists mainly of silt and very fine sand, sometimes interlaminated with coarser sand. Because the colluvium was not broken before 1987, we know the colluvium was deposited after the previous slip had occurred.

Offset Features

Elmore Ranch Fault (Main Strand)

A series of features at site 1 (Fig. 2), demonstrate that slip occurred on the main strand of the Elmore Ranch fault before 1987 but since deposition of the lake sediments. The primary evidence is a wedge of Lake Cahuilla recessional berm deposits that fell into and filled a pull-apart fracture that formed previous to slip in 1987. The site and excavation maps (Fig. 3a) identify the location of the pull-apart feature relative to documented measurements of 1987 slip. The average of two 1987 slip measurements, one on either side of the feature we studied, is 70 ± 5 mm. Edges of the pull-apart feature, shown in Fig. 3b, are offset left-laterally by 300 ± 20 mm. This measurement of offset is the sum of two distances between distinct and unambiguous piercing points on either side of a block that fell into the collapse fissure (Fig. 3). Reducing this value by 70 ± 5 mm (the 1987 slip along about the same strike) leaves 230 ± 20 mm of left-lateral offset that accumulated across the pull-apart feature previous to 1987. Fig. 3c is a trench log of an exposure immediately southwest of the pull-apart. It shows a wedge of colluvium in the fault zone, deposited there before 1987 and overlying a pull-apart feature in the underlying surface. This exposure provides evidence that the pull-apart opened after deposition of the Lake

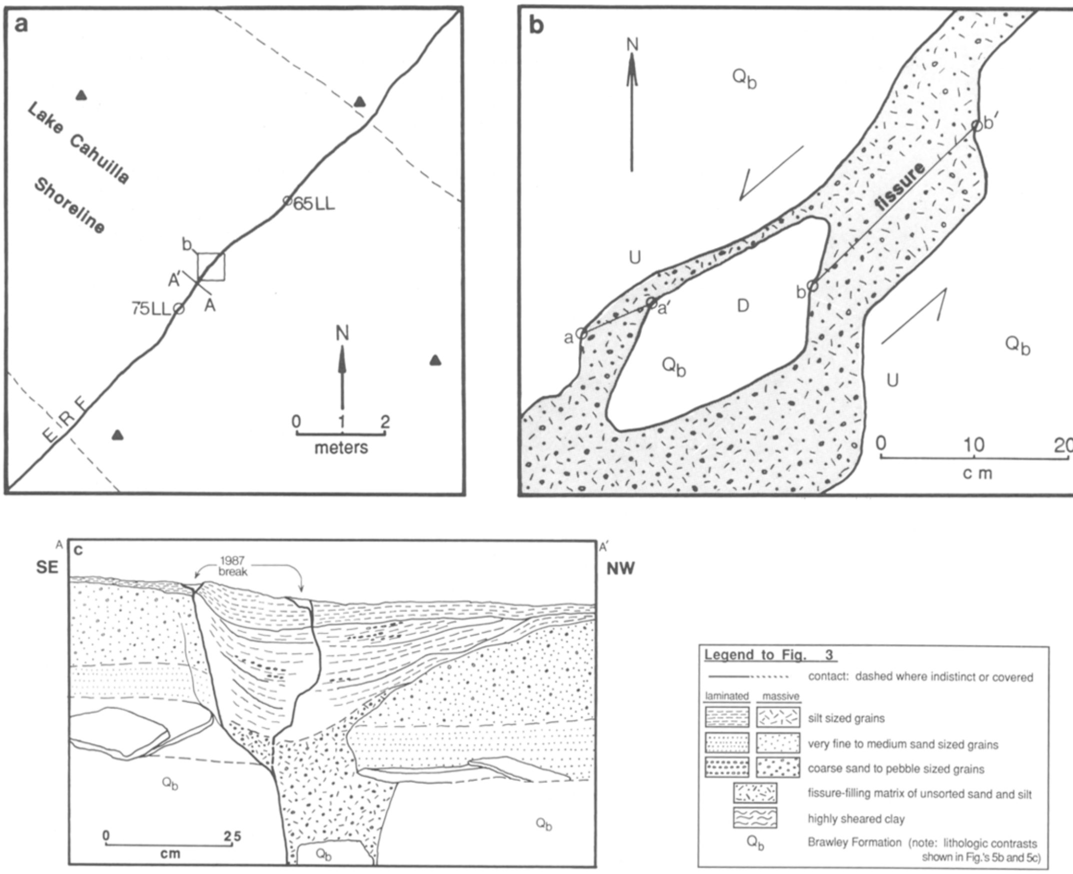

FIG. 3. (a) Site 1 study area on the main strand of the Elmore Ranch fault, where the fault cuts a recessional berm. This berm, at about 17 m below sea level, was deposited as Lake Cahuilla was desiccating about 330 years ago. Two slip measurements across pull-aparts formed during 1987 slip are reported in millimeters of left-lateral (LL) displacement. The shaded region shows the limits of our excavations. (b) Feature across which total slip was measured. Location of this feature is about half a meter northeast of cross-section A-A′. The abrasion surface cut into blocks of disrupted Brawley formation (Q_b) has been offset, forming a pull-apart with a central block that dropped down into the fault fissure. The fissure is filled by unsorted silt to pebble-sized clasts, derived from the overlying Lake Cahuilla deposits. The total left-lateral slip was obtained by summing the slip from piercing points a-a′ (75 mm) and b-b′ (225 mm). (c) View to the southwest towards a wall of excavation, labelled A-A′ in map of study area. This exposure shows that Lake Cahuilla berm deposits collapsed into the fissure that formed during slip previous to 1987. The fissure was progressively filled by laminae of silt and sand, and it had filled completely before the 1987 fault rupture. The 1987 rupture broke both along the margin and through the fissure fill, which had not been previously faulted. Slabs of sandstone overlie the abrasion surface and underlie the recessional berm deposits.

Cahuilla sediments and was subsequently filled by colluvium. The collapse feature had been filled completely previous to 1987 rupture. Vertical separation apparent in this figure is a local effect of the uneven abraded surface of the Brawley formation; the piercing points at this site showed insignificant vertical displacement. The nature of the colluvial wedge suggests pre-1987 slip occurred before its deposition and probably in a single event. If the fissure had opened in increments, during two or more events, we would have expected to see upward truncations of faults within the fissure fill. Because the fissure fill seems to have been faulted only by the breaks that occurred in 1987, the fissure probably formed in one event.

Log of SW Trench Wall

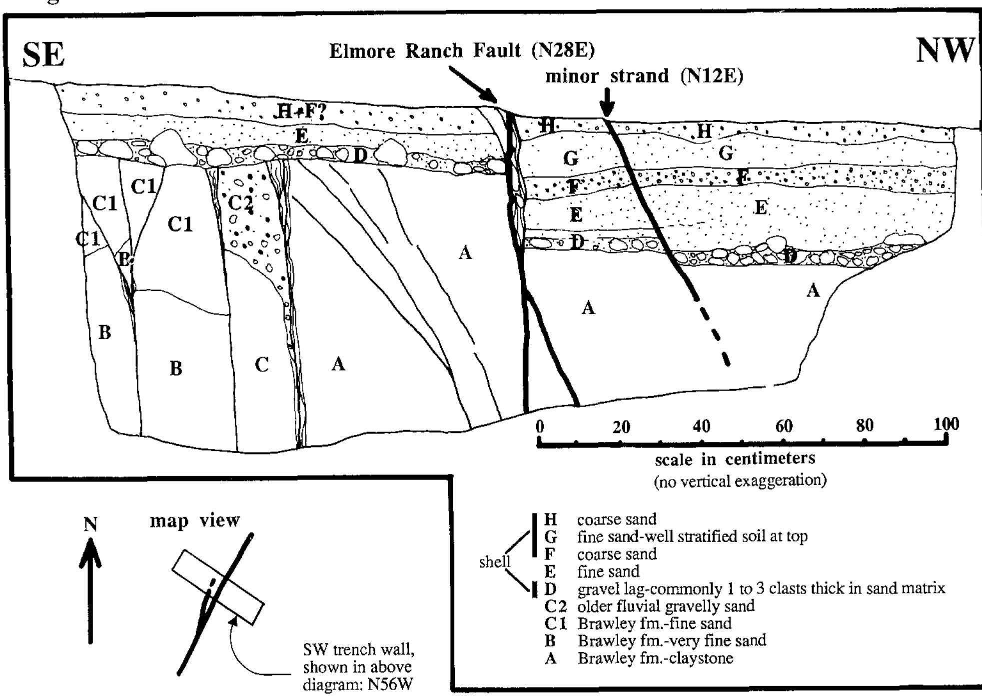

FIG. 4. Site 2 on the main strand of the Elmore Ranch fault. The abrasion surface and presumably late Holocene alluvium units D through H show much larger vertical separation than the minor vertical separation observed here in 1987. It is not clear whether these deposits are associated with the latest highstand of Lake Cahuilla, thus any correlation of this offset to the pre-1987 slip observed at site 1 is tenuous.

Elmore Ranch Fault (Main Strand)

Excavations at site 2 (Fig. 2), also on the main strand of the Elmore Ranch fault, revealed vertical separation of alluvium and an underlying conglomerate unit (Fig. 4). These deposits overlie the abrasion surface, but their age is poorly constrained. The alluvium and conglomerate units are probably all late Holocene. There is clearly evidence for vertical separation previous to 1987, but no data on pre-1987 horizontal separation was obtained at this site. If the vertical separation at site 2 occurred in the same event documented at site 1, then the behavior of the fault at site 2 was different in the past two events because slip in 1987 was mostly left-lateral at this location.

The deposits at site 2, however, could be substantially older than the last highstand. For instance, it is possible that the latest highstand did not reach the elevation of this site, in which case the abrasion surface itself may have last been modified much earlier than the surface at our other sites. In this case the vertical displacement may correspond to a larger horizontal displacement accumulated over a longer interval.

Western Elmore Ranch Fault

Site 3 (Fig. 2) on the western strand of the Elmore Ranch fault provided useable piercing points across a pull-apart that show this strand also slipped before 1987.

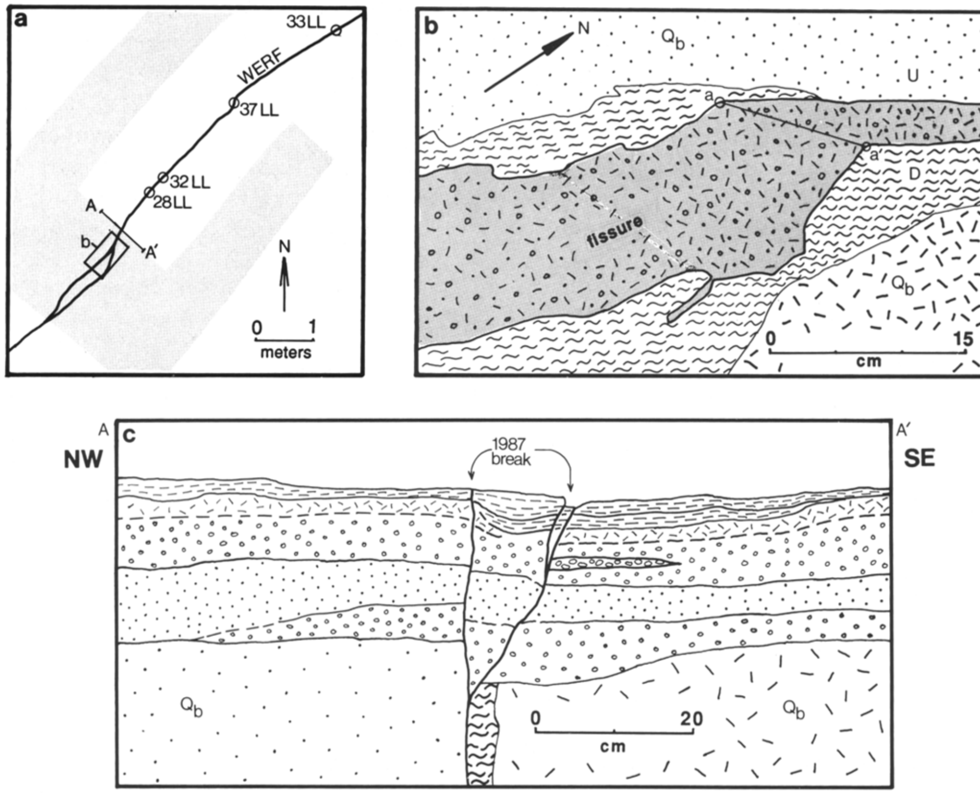

FIG. 5. Excavation site 3 on the Western Elmore Ranch fault (WERF). Note that dip-slip motion here is opposite (southeast side down) to that at site 2 (northwest side down). For legend refer to Figure 3.

At this site (Fig. 5a), we found a pull-apart feature (Fig. 5b) underlying a collapsed wedge of recessional berm deposits and filled by colluvium (Fig. 5c). The geological relationships at site 3 are thus similar to those at site 1. At site 3, slip in 1987 was 30 ± 5 mm left-lateral, again the average of two nearby measurements. In 1987, the component of dip-slip movement was smaller than 5 mm. Again, the collapse feature overlying the pull-apart had been completely filled previous to 1987.

The pull-apart at site 3 had two correlable offset corners, and slip vectors measured across both of these indicated a significant vertical component in the pre-1987 slip. The total slip vector across piercing point a-a′ had an azimuth of N52°E, a plunge of 24°NE, and a length of 130 ± 5 mm. This resolves to 119 mm of left-lateral and 53 mm of dip slip along a N52°E trend. Left-lateral slip (along the same azimuth) of 30 ± 5 mm attributed to 1987 rupture is then subtracted from this to obtain the pre-1987 slip vector. Pre-1987 slip on this strand thus involved about 90 ± 10 mm of left-lateral slip, and about 53 ± 5 mm of southeast-down dip slip.

Eastern Elmore Ranch Fault

On the eastern strand of the Elmore Ranch fault (Fig. 2), 1987 slip was 50 ± 10 mm where it crossed an approximately 1 m thick recessional berm only about 150 m southwest of the power-line road. Our preliminary excavations at site 4 (Fig. 2) indicate that this strand did not slip in the 330 years previous to 1987. Although locally pre-1987 collapse of recessional berm sands and colluvium into minor fractures along the fault is apparent, we have not found evidence for pre-1987 displacement like the pull-apart features that we found on the other two strands of the Elmore Ranch fault. Also, the pull-apart identified in the abrasion surface shows only 60 ± 5 mm left-lateral slip, within the range of 1987 measurements. From our preliminary work here pre-1987 and post-latest highstand slip appears to be less than about 25 mm. A parallel strand, roughly 50 m northwest of this one, may have slipped previous to 1987, but this possibility has not yet been investigated.

Other Sites

Exploratory hand trenches were dug along the main strand of the Elmore Ranch fault both northeast and southwest of site 1. These excavations have proved inconclusive. Portions of Kane Spring fault, Eastern Kane Spring faults, and the Lone Tree fault that slipped in 1987 do not cross the distinct berms at −15 to −18 m elevation. Promising sites where these strands cut other Lake Cahuilla berm sediments have not yet been identified. Similarly, we have not yet found potential study sites on mapped cross-faults that did not rupture in 1987. Further study of previous slip on these and other cross-faults in this area may provide constraints on questions raised by the data obtained so far.

Discussion

Our data demonstrate that the Elmore Ranch cross-fault zone slipped in the ~330 years before 1987. The Superstition Hills fault also ruptured during the same time interval (Hudnut and Sieh, 1989). Thus triggering of the Superstition Hills earthquake by the Elmore Ranch earthquake (Hudnut *et al.*, 1989b) may also have occurred in previous events. Our data are consistent with a characteristic doublet, yet allow other fault interaction models over several earthquake cycles.

Comparison of Penultimate Slip to Slip in 1987

Pre-1987 slip observed on the western strand and on the main strand of the Elmore Ranch fault are expressed by similar geological relationships. Both strands offset features of the same age and contain collapse features that were completely filled with colluvium before 1987. Moreover, neither of the sites show evidence of multiple slip events. Thus, the data suggest simultaneous ruptures, but do not rule out other possibilities. Simultaneous rupture in 1987 shows that it is certainly possible that both the western and main strands of the Elmore Ranch fault slipped in one penultimate event. The total pre-1987 slip of 320 ± 30 mm on the three strands of the Elmore Ranch fault was over twice the total slip of 150 ± 20 mm at these sites in 1987. The eastern strand apparently did not slip in the previous slip event.

Another notable difference between the penultimate and 1987 slip events is the 53 ± 5 mm vertical component (southeast down) on the western strand during previous slip. None of the cross-faults had significant dip-slip in 1987 at the sites we studied. The total vertical separation at site 2 is large and may result from slip accumulated over more than a few hundred years. The sense of dip-slip at site 2 is also opposite (northwest side down) the sense of dip-slip found at site 3 on the western strand.

Some of the cross-faults had been mapped previously as normal faults with southeast-down movement (R. Sharp and J. Lienkaemper, personal comm., 1987). This sense of slip has now been observed only for pre-1987 slip on the western strand. On the Elmore Ranch fault zone, there was no consistent dip-slip component observed in the 1987 surface slip (Hudnut *et al.*, 1989b). Teleseismic waveforms yield fault plane solutions consistent with dominantly lateral motion (Sipkin, 1989; J. Pacheco, personal comm., 1988), although the northwest-trending nodal plane has not yet been well constrained. Thus, a dip-slip component may be present in the 1987 cross-fault event, and it is possible that dip-slip in the penultimate event on the west strand is tectonically significant. We instead prefer to interpret the pre-1987 vertical component as local half-graben tilting within the fault zone, with left-lateral slip on the main strand of the Elmore Ranch fault dominating the active tectonics.

Slip Rate Estimates

The slip rate across the Elmore Ranch fault zone can be estimated for two end-member cases: (1) pre-1987 slip occurred soon after the latest highstand, and (2) pre-1987 slip occurred as recently as mid-1915 (see discussion of historical data, Hudnut and Sieh, 1989). Using these bounds, we estimate a slip rate between 0.5 and 1.5 mm/yr for the Elmore Ranch fault zone (including the main, western, and eastern strands). By the same method, Hudnut and Sieh estimate a slip rate between about 2 and at least 6 mm/year for the Superstition Hills fault. Afterslip is not considered for the Elmore Ranch fault zone, however, because none has yet been observed (Hudnut *et al.*, 1989b).

Correlation Between Penultimate Slip Events on the Elmore Ranch Fault and Superstition Hills Fault

Pre-1987 slip on strands of the Elmore Ranch fault occurred after a date within the range 1663 ± 22 A.D. and probably before mid-1915. The previous slip on the Superstition Hills fault at the Imler Road trenching site also occurred within this period (Hudnut and Sieh, 1989). Because the surface ruptures of 1987 occurred on both the cross-faults and the Superstition Hills fault, pre-1987 slip on the cross-faults and Superstition Hills fault may also have been produced in a single sequence of earthquakes. However, pre-1987 slip at the cross-fault sites during the penultimate event was greater than in 1987 by a factor of 2, whereas pre-1987 slip on the Superstition Hills fault may have been less than in 1987 (Hudnut and Sieh, 1989). Despite these differences, previous surface slip on the main fault was greater than previous slip on the cross-faults, so the main fault event was presumably the larger of the two previous events.

The question of timing between the penultimate slip events cannot be answered yet. Radiocarbon dating may be possible, but we have not yet found carbon in the younger units. Also, unfortunately, radiocarbon dates from the past few hundred years are commonly ambiguous (e.g., Sieh *et al.*, 1989).

Because the data do not fully constrain the temporal relation between previous slip events on the cross-faults and main fault, alternatives to the behavior observed in 1987 are possible. The earthquake recurrence diagrams in Figure 6 illustrate some of the possibilities. In the first model (Fig. 6a) the 1987 sequence is characteristic and recurs periodically. The data are consistent with such a characteristic doublet only if the total slip per event is allowed to vary by a factor of 2. These diagrams represent stress accumulation and stress drop inferred from the hypo-

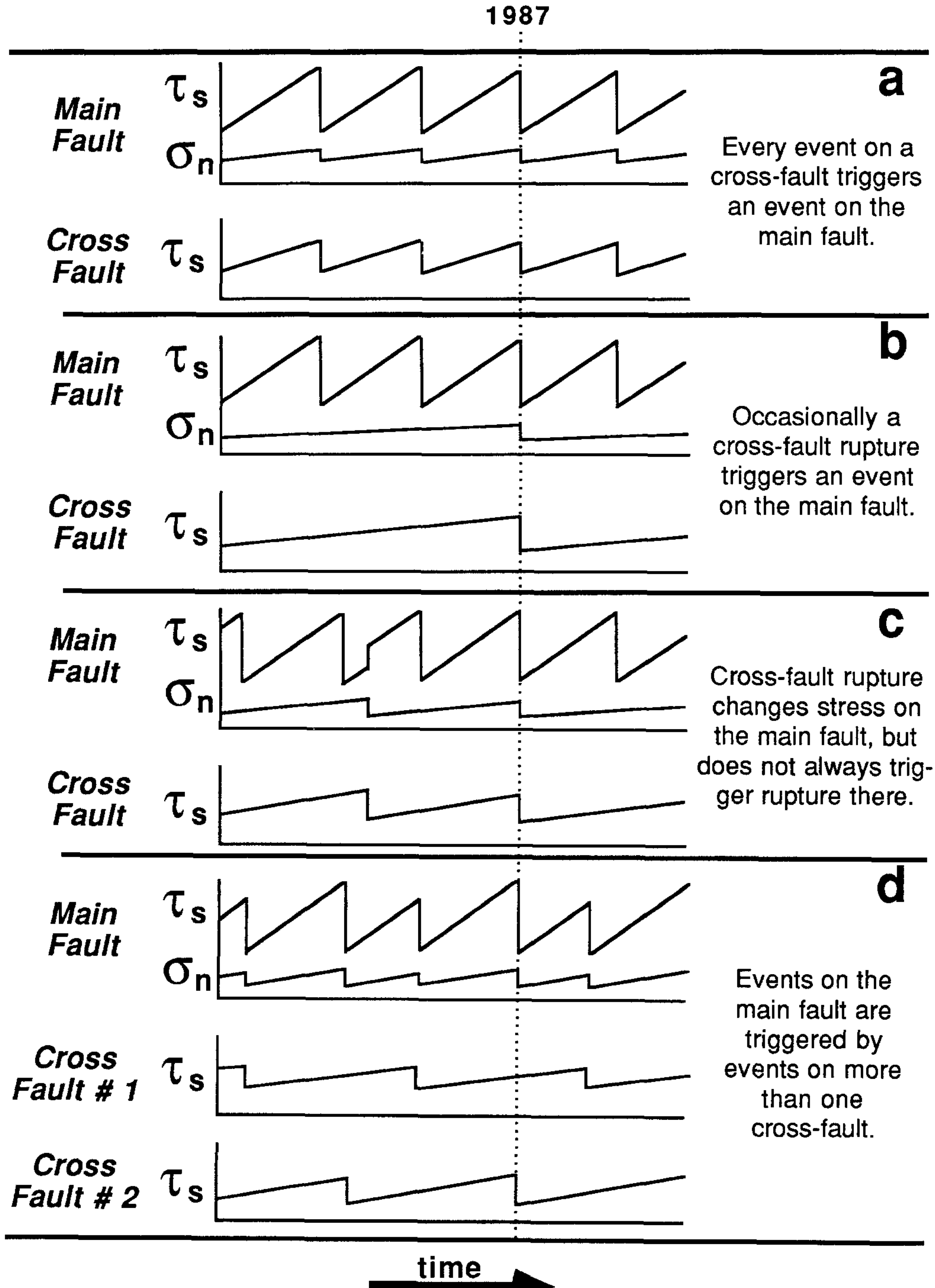

FIG. 6. Hypothetical interactions between cross-faults (e.g., the Elmore Ranch fault zone) and main fault (e.g., the Superstition Hills fault) over several earthquake cycles. Vertical axes show shear stress (τ_s) and normal stress (σ_n) on the faults, and the horizontal axis represents time. We consider case 'a' the simplest explanation of the observations.

thetical displacement history of the faults. The main points of Figure 6 are that other possibilities can explain the available data, and that other interacting fault systems may behave differently.

If rupture on the Elmore Ranch fault always leads to triggering of the Superstition Hills fault by a decrease in normal stress, the system of faults is presumably coupled and one aspect of its behavior is easily predictable; the recurrence of cross-fault slip events will dominate recurrence intervals on the main fault.

CONCLUSIONS

This paper demonstrates that slip occurred previous to 1987 and since ~1660 A.D. on both the western and main strands of the Elmore Ranch fault, and discusses the preliminary result that the eastern strand did not have significant rupture during the same interval. Left-lateral slip on the western and main strands before 1987 was greater than slip in 1987 at these two sites. Dip-slip previous to 1987 on the western strand is interpreted as tectonically insignificant. A slip rate of from 0.5 to 1.5 mm/yr and average recurrence interval of from 150 to 300 years are estimated for the Elmore Ranch fault zone. This range in average recurrence is identical to that determined for the Superstition Hills fault (Hudnut and Sieh, 1989). The estimated slip rate, however, is only about one fourth of the rate they calculated for the Superstition Hills fault.

Both the Elmore Ranch fault and Superstition Hills fault slipped once between the times of the latest Lake Cahuilla highstand and 1915. Therefore, it is possible that the 1987 sequence may be the repeat of a previous earthquake sequence. If so, one difference between these sequences is that the total cross-fault slip in 1987 was smaller, whereas slip on the Superstition Hills fault may have been larger than in the previous sequence. Although cross-fault ruptures can trigger main fault ruptures as occurred in 1987, the 1987 sequence may have been a rare occurrence of an unusual mechanism. The available data do not resolve this issue, but they do permit that the penultimate events on these faults may also have occurred as a doublet.

Both 1987 surface displacements and prehistoric slip show that left-lateral slip is the dominant component of the slip vector on the cross-faults. Dip slip has been a relatively minor component during the past 330 years on the Elmore Ranch fault zone. This observation contradicts tectonic models of the Salton trough that compare this region with a mid-ocean ridge setting (e.g., Lomnitz *et al.*, 1970). A stepover between major transform faults (the San Andreas fault and Imperial fault) should correspond with a ridge (and normal faults with extension parallel to the transforms), rather than with strike-slip motion as observed on the Elmore Ranch fault.

ACKNOWLEDGMENTS

Location and working of trenching sites were assisted by J. Goodmacher and D. Valentine. S. Lindvall and A. Thomas helped in the excavations, as did R. Klinger and R. McElwain in the early stages. Nearly a year before the earthquakes, P. Williams suggested to us the potential use of Lake Cahuilla deposits in our studies of slip on these cross-faults. We thank K. Sieh, N. Christie-Blick, and D. Simpson for reviews, and R. V. Sharp for his comments. Research supported by U.S. Geological Survey grant No. 14-08-0001-G1330. Lamont-Doherty Geological Observatory Contribution No. 4420.

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Manuscript received 27 October 1988